ARTICLE IN PRESS

Egyptian Journal of Petroleum (2016) xxx, xxx–xxx

HOSTED BY

ELSEVIER

Egyptian Petroleum Research Institute

Egyptian Journal of Petroleum

www.elsevier.com/locate/egyjp
www.sciencedirect.com

FULL LENGTH ARTICLE

Feasibility study for biogas integration into waste treatment plants in Ghana

M. Mohammed [a], I.S. Egyir [b], A.K. Donkor [c,*], P. Amoah [d], S. Nyarko [c], K.K. Boateng [e], C. Ziwu [c]

[a] Institute for Environment and Sanitation Studies, IESS, University of Ghana, Box 209, Legon, Accra, Ghana
[b] Department of Agricultural Economics and Agribusiness, University of Ghana, Box LG68, Legon, Accra, Ghana
[c] Department of Chemistry, University of Ghana, Box LG56, Legon, Accra, Ghana
[d] International Water Management Institute, IWMI, West Africa Office, Accra, Ghana
[e] Department of Material Engineering, Kwame Nkrumah University of Science and Technology, KNUST, Kumasi, Ghana

Received 2 June 2016; revised 31 August 2016; accepted 13 October 2016

KEYWORDS

Biogas;
Sewerage;
Renewable energy;
Cost-benefit analysis;
Internal rate of return;
Ghana

Abstract Biogas (anaerobic digestion) technology is one of the most viable renewable energy technologies today. However, its economic efficiency depends on the investment costs, costs of operating the biogas plant and optimum methane production. Likewise the profit level also rests on its use directly for cooking or conversion into electricity. The present study assessed the economic potential for a 9000 m^3 biogas plant, as an alternative to addressing energy and environmental challenges currently in Ghana. A cost-benefit analysis of the installation of biogas plant at University of Ghana (Legon Sewerage Treatment Plant) yielded positive net present values (NPV) at the prevailing discount rate of 23%. Further the results demonstrate that installation of the plant is capital intensive. Biogas used for cooking was by far the most viable option with a payback period (PBP) of 5 years. Sensitivity analysis also revealed cost of capital, plant and machinery as the most effective factors impacting on NPV and internal rate of return (IRR).

1. Introduction

Biogas is considered one of the alternative energy sources and is produced through anaerobic digestion from raw materials, such as agricultural residues, animal waste, municipal wastes and industrial wastes [1]. Energy generated from these sources via anaerobic digestion reduces atmospheric methane emissions and production of digestate. A number of studies have proved the effectiveness of this technology to manage organic waste [2–7] in an environmental-friendly and cost-effective manner [8–11].

Regardless of these successes and the existence of favourable conditions for its generation in developing countries, specifically in Sub-Saharan African countries, the promotion and the development of the technology have suffered a setback. These setbacks have been partly attributed to failure of governments to support the technology through a focused energy policy, lack of information regarding its economic

* Corresponding author.
E-mail address: akdonkor@ug.edu.gh (A.K. Donkor).
Peer review under responsibility of Egyptian Petroleum Research Institute.

http://dx.doi.org/10.1016/j.ejpe.2016.10.004
1110-0621

viability, poor design and construction of digesters, wrong operation and lack of maintenance by users. Both operators in the industry and users have identified operation and maintenance, and after sale service as the major causes derailing the speedy adoption of the technology in most developing countries including Ghana [12]. Unlimited literature exists on the factors affecting the development, promotion and adoption of biogas energy. The most extensive has been carried out on social factors [13–15], economic factors [14,16], technical factors [16,17] and organizational factors [18].

The biogas production processes have the advantage of low energy requirement for operation, low initial investment cost and low sludge production when compared to the conventional aerobic processes [19]. The technology (biogas) has proven to be a modern energy source that has improved the life of many who have used it for decades [20] as it is less capital intensive. It is noted for generating energy, improving sanitation, and supplying nutrient rich organic fertilizer. Despite the ready availability of biogas resources, relatively few studies have focused on the economic assessment of biogas plants in ascertaining the financial viability of installing biogas plants both at the households and institutional level. A number of studies have been conducted providing information on design and investment of biogas digesters in developed countries but this is not the case for developing countries [7,21]. Nelson and Lamb [22] presented a comparison of projected and actual costs of constructing a biogas digester on a Minnesota dairy farm in the USA, the net returns from electricity annually and the payback period for the investment of the digester were evaluated. Meyer and Lorimor [23] evaluated the construction costs for two biogas digesters and estimated an 11.4% "return on investment". The capital cost of biogas plants often varies with the size of plant, as well as availability of local material. Many studies have indicated that the operating or running cost of a biogas plant is estimated at 1–1.5% of the total construction or capital cost [24]. In a study by Adeoti et al. [25] the breakdown of the first cost of the biogas plant designed in Nigeria revealed that construction costs took about 65% while facilities, installation, labour and land accounted for the remaining 35%.

The World Health Organization (WHO) has prepared guidelines on conducting cost-benefit analyses of household biogas plants, as well as published cost-benefit analyses [31]. Unlike many other renewable energy technologies (RETs) almost all expenses need to be financed upfront, with very low operating expenses (operation and maintenance costs) thereafter. Thus, the economy of an anaerobic digestion (AD) technology is characterized by high initial investment costs which will result in savings (non-monetary) with less recovery of capital investment.

There are various economic analytical tools that have been used by different researchers for estimating the financial viability of biogas projects. Some are Life Cycle Assessment (LCA), Local Economic Impact (LEI), cost-benefit analysis (CBA), Cost Effectiveness Analysis (CEA), Economic/Financial Valuation (EV), conjoint analysis and real options [32]. Unfortunately, none of these techniques have been given more attention than cost-benefit analysis where investment appraisal of project is concerned based on efficiency criteria. Hosking and Du Preez [33] referred to CBA as a standard method of comparing the social costs and benefits of alternative projects or investments. Costs and benefits in this context are measured and then weighed up against each other in order to generate criteria for decision-making. This is now very popular in many sectors. Additionally, Marchaim [34] suggested three major areas of applications in assessing the financial viability of biogas plants: individual household units, community or institutional plants and large-scale commercial operations. In each of these cases, the financial feasibility of the facility depends largely on whether outputs in the form of gas and slurry or digestate can substitute for costly fuels, fertilizers or feeds which were previously purchased, while at the same time abating pollution [35].

In Ghana, the technology began to gain interest in the 1960's to help curb energy crisis. According to Netherlands Development Organization (SNV) [26] the country has the potential of realizing about 280 thousand domestic plants capable of producing about 6000 m^3 of liquid fertilizer daily and biogas effluent is estimated to increase agricultural production by 25%. The first biogas demonstration plant – a 10 m^3 Chinese fixed dome digester – was constructed in 1986 by the Ministry of Energy, with support from the Chinese government. Subsequently other plants were installed with the support of international organizations by the Ministry of Energy, for example, the Apollonia biogas plant which provided electric power for domestic use and bio-slurry for agriculture [27].

Despite these numerous set ups, there is scarcity of data on the financial viability of biogas plants. Most studies so far have focused on the adaptation and development of the technology for bio-sanitation interventions without energy recovery from the system [26,28–30]. Accordingly, this study ascertains the financial viability of an institutional installation of a biogas plant at University of Ghana, Accra with the option to be utilized for cooking or electricity generation.

2. Materials and methods

2.1. Study area, project description and data

Accra, the capital city of Ghana, is located between latitudes 4° and 11.5° North and longitudes 3.11° West and 1.11° East. The landscape is low-lying, 20 m above sea level with few short irregular hills and depressions in some parts of the city. About 15% of Accra is served by conventional sewerage network. Outside the sewered areas, septic tanks, public toilets, pit latrines and pan latrines are also used. Presently, less than 25% of all the sewerage treatment plants within the Accra Metropolis are functioning [37].

As part of efforts to limit or prevent the indiscriminate discharge of untreated sewage into the sea and also to resolve environmental problems in the city, the African Development Bank assisted the Ghana Government to build two (2) new sewage treatment plants, one at the University of Ghana, Fig. 1. This plant with a capacity of (9000 m^3/day) is expected to serve over 33,000 people [36]; this will receive wastes from the University of Ghana and its environs. The treatment concept of the proposed project is based on waste stabilization ponds with effluents discharging directly into the sea.

Detailed data on inputs of the most adopted dome type biogas design in Ghana were sourced from Biogas Technologies Africa Limited (BTAL), and used to arrive at various costs and benefits involved. The capacity of the plant was estimated

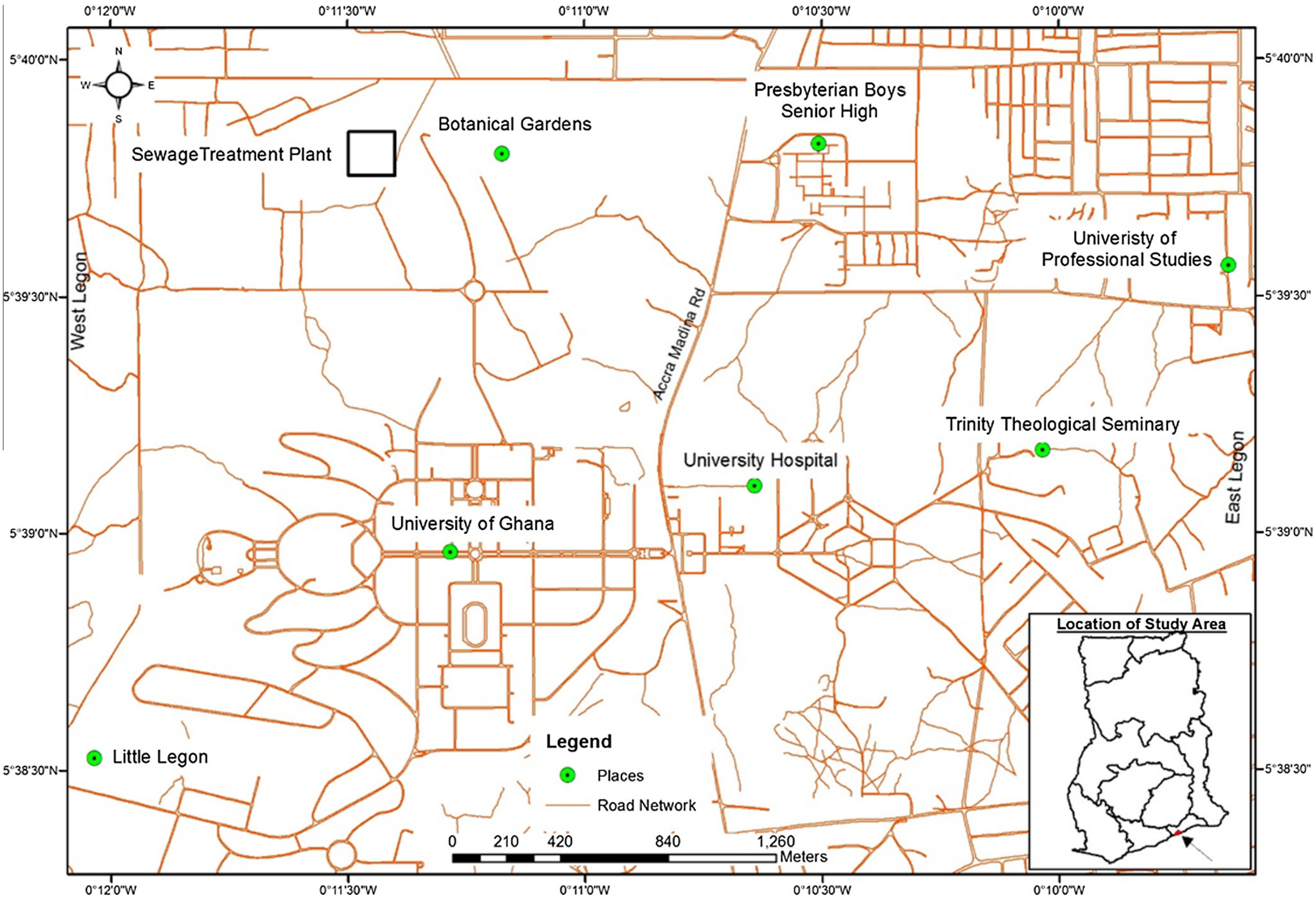

Figure 1 Legon sewerage treatment plant (Accra). Google Earth.

based on the waste generated by the population feeding the sewerage treatment plant. The benefits generated have been estimated for two cases. The first case assumes that biogas generated will be used in gas stoves with 80% maximum efficiency and will replace energy from liquefied petroleum gas (LPG). In the second case, it assumes that biogas generated will be used for electricity generation in gas generators (GENset) having an efficiency of 35%.

2.2. Economic assessment

2.2.1. Conceptual framework

In this study, it was assumed that the project is an investment activity where capital resources are expended to generate an asset from which benefits will be accrued over an extended period of time i.e. the financial viability of the biogas plant was based on cash flow [38–40]. The conceptual framework is outlined in Fig. 2 below. The total costs and total benefits were identified and valued based on the technological design (dome type biogas plant). This was justified by work of Bensah and Brew-Hammond [12] and Washenfelder [41], that 80% of biogas plants disseminated in Ghana are based on the dome design. The costs and benefits (known as revenue) were discounted as it was assumed that the value of currency undergo changes as the years go by [38]. The discounting considered the lifespan of the plant and a discount rate which is dependent on the financial market conditions of the economy. An overall financial viability of biogas plant was then undertaken by the use of financial decision criteria commonly used to estimate the viability of investment opportunities. These included net present value, internal rate of return and payback period [38,42].

2.2.2. Estimating the cost of the biogas plant

The cost elements included the total fixed or investment cost and total variable cost. The cost estimation was made at 2012 market prices by looking at the estimates from a reputable biogas firm in Ghana as a reference point. To further simplify the estimations, the cost elements were categorized into preliminary expenses i.e. pre-production expenditures, cost of equipments, biogas use systems and accessories and environmental protection (Table 2). As indicated in previous research by Kandpal et al. [43], the capital cost of biogas plants often varies with the size of plant; therefore for the analysis presented in this study, a figure of 1% of the capital cost was assumed to be adequate for the operation and maintenance cost [44,45]. The capital cost of a biogas digester constructed by BTAL is \$300 per cubic metre of digester. This includes administrative, transport costs and consultancy fees. A major item of the fixed cost element that differentiates the cost involved in cooking option and electricity generation is the cost of the industrial stove and genset generator.

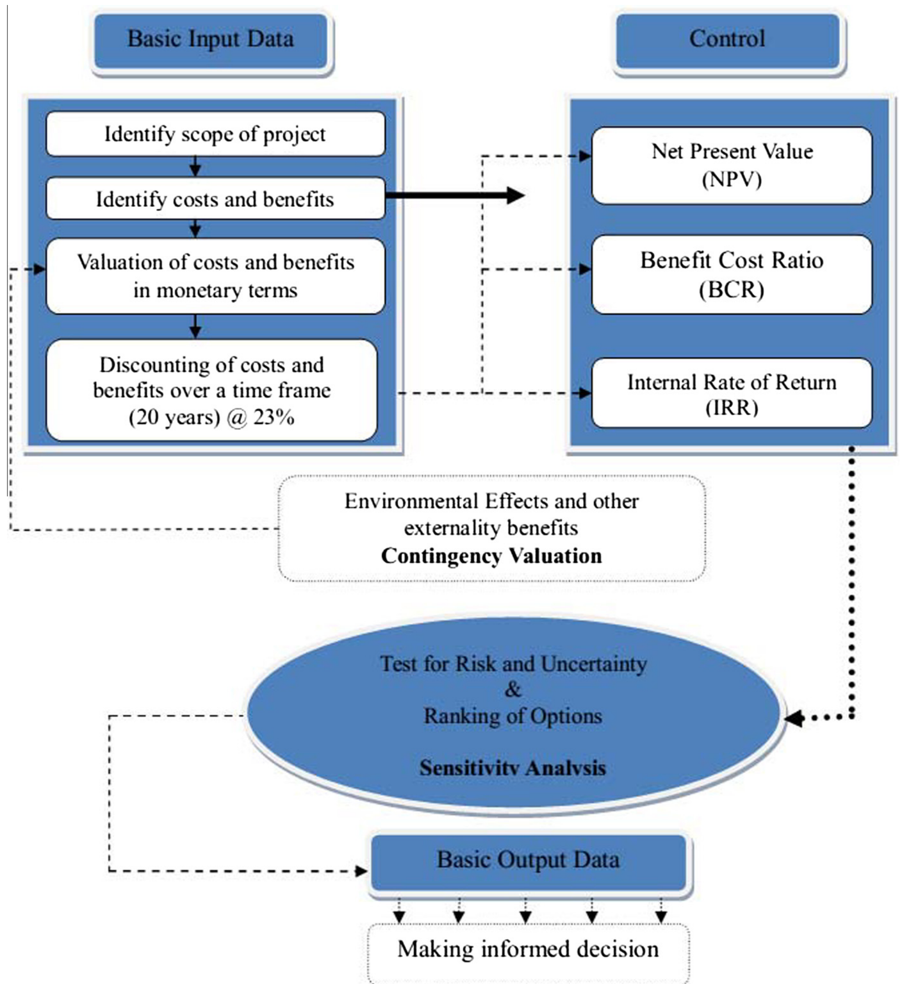

Figure 2 CBA conceptual framework.

2.2.3. Estimation of benefits of the biogas plant

Annual income was calculated according to the annual expenditure savings on alternative fuel, the sale of digestate (fertilizer), annual cost savings from water recycle, cost savings from avoidance of septic tank construction and annual potential earnings from carbon markets (CER credits). The assumption was that the client will only begin to enjoy the benefits of the cost that is saved for the avoidance of cesspit emptying in the second year (which is the general assumption in Ghana) after the installation of the plant used in the cash flow analysis. A cash flow table was developed for a period of 20 years based on the lifespan of the plant. A discounted cash flow was estimated at a discount rate of 23% based on the Ghana Commercial Bank average interest rate for year 2012. The exchange rate was 1.90 Ghana cedis per USD. The resulted cash flow analysis was evaluated under two scenarios (cooking and electricity generation).

A summary of the parameters used in estimating biogas generation is shown in Table 1. The plant investment was estimated based on the 2012 unit charge of Liquefied Petroleum Gas (LPG) ($ 0.59 per kg) and the unit sale of electricity (current PURC approved tariffs at $ 5.26 per kVA per month). The assumption was that the fertilizer produced from the filtered digestate will be sold to farmers at $ 6.59 per 25 kg (Wienco Company Ltd., the largest fertilizer dealer quoted this price for farmers in Ghana for 2012) as well as treated water that could be reused for flushing toilets.

2.2.4. Sensitivity analysis

A sensitivity analysis using estimated financial values was conducted to systematically test what would happen to the earnings capacity of a project, in this case, the biogas plant, if events changed from that used in the initial planning of the project. This was done as a means of dealing with uncertainty about future events and values [38] as they are many assumptions and uncertainties involved in cost benefit analysis [43]. This was achieved by varying the input variables, cost and the benefits elements such as discount rate, capital cost, operation and maintenance cost of the project and, the effect on the outcome of the project worth was determined. The results were then presented in tables and tornado charts (see Table 4).

2.2.5. Cost-benefit analysis

The internal rate of return (IRR), the net present value (NPV), the benefit cost ratio (BCR) and the payback period (PBP) were used to assess the financial viability of the biogas plant [38]. The NPV was calculated as follows:

$$\mathrm{NPV} = \sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+r)^t} \quad (1)$$

Table 1 Summary of parameters used for calculation of 9000 m^3 from BTAL.

Parameter	Unit	Value
Process temperature	°C	35
Population serving the digester	persons/day	33,000
Per capita sewage generation	m^3/person/day	0.009
Organic component MSW generation	%	50
Degradable organic MSW	kg/person/day	0.50
Per capita annual generation	m^3/person/day	0.0099
Biogas density	kg/m^3	0.940
Biogas mass rate	kg/year	111,777
LPG equivalent of biogas for cooking	kg LPG/m^3	0.40
Biogas equivalent of LPG generation per day	kg/day	130
Retention period	Days	30
Average cost of digester and infrastructure	\$/m^3 (BASE)	300
Biogas-based electricity generator (500 kW)	\$/4 PCS	720,000
Household family stove	\$	7000
Methane	%	60
Methane emissions prevention/avoidance	Tonnes	67.07
Carbon market	\$/tonne	10.00

Table 2 Summary of capital cost for cooking and electricity generation from biogas plant.

Components of capital cost	Cost estimates (\$'000)	
	Cooking	Electricity generation
Preliminary expenses (pre-production expenditures)	135	135
Plant machinery and equipment (digester and infrastructure)	2700	2700
Biogas used systems and accessories	160	1603
Environmental protection	11	19
Contingencies	266	266
Total	3304	4723

where:Ct – Costs in year t; Bt – Benefits in year t; r – discount (interest) rate; t – number of years from the present (1, 2,... 20).

The IRR refers to that discount rate which makes the NVP of the cash flow equal zero or the average earning power of the expenses incurred in the project over the project life was estimated as follows:

$$\mathrm{IRR} = \sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+r)^t} = 0 \quad (2)$$

Likewise, the profitability as ratio of expected income to investment was calculated with the formula:

$$\mathrm{BCR} = \sum_{t=0}^{t=n} \frac{B_t}{(1+r)^t} \Bigg/ \sum_{t=0}^{t=n} \frac{C_t}{(1+r)^t} \quad (3)$$

The payback PBP defined as the number of years necessary to recover the investment made and it was estimated with the following formula:

$$\mathrm{PBP} = 1 \Bigg/ \sum_{t=0}^{n} E_{n=1} \quad (4)$$

where: I-initial investment of the project and; E- the projected net cash flows per year from the investment.

3. Results and discussion

3.1. Investment costs and benefits

The cost-benefit analysis was conducted using 9000 m^3 digester based on the population to feed the wastewater plant. The annual biogas production of 118,912 m^3/annum and per capita annual biogas generation of 0.0099 m^3/person/day led to 47,450 kg of biogas equivalent of LPG generation per annum. As can be seen in Table 1, the unit cost of a digester in Ghana is \$ 300/m^3 with the total cost of investing in a unit biogas plant amounting to \$370 (cooking option) and \$530 (electricity generation option). The least cost item for the two scenarios was the environmental protection with plant machinery and equipment, and biogas used systems and accessories constituting 90% of the total cost of the project for electricity generation option (Fig. 3). This was in contrast with Adeoti et al. [25] observation where plant machinery and equipment contributed 35% of the total cost of the project for the cooking option. Therefore considering the initial cost needed for the installation of the biogas plant, it was concluded that the project is capital intensive.

3.2. Cost-benefits analysis

The biogas plant has the potential to save the cost on cesspit emptying of 7207 trips/year which would amount to a value of \$468,440 per annum when operating at full capacity. Savings from water recycling (treated wastewater) (60% domestic usage in water closet) at 64,861 m^3/year would also amount to \$49,806. The installation of biogas plant also has the potential to replace 100% septic tanks at \$230/m^3. The production of electricity from biogas leads to reduction of GHG emission and Ghana as a signatory to the Kyoto Protocol in Montreal is qualified to submit certificates (Certified Emission Reduc-

Please cite this article in press as: M. Mohammed et al., Feasibility study for biogas integration into waste treatment plants in Ghana, Egypt. J. Petrol. (2016), http://dx.doi.org/10.1016/j.ejpe.2016.10.004

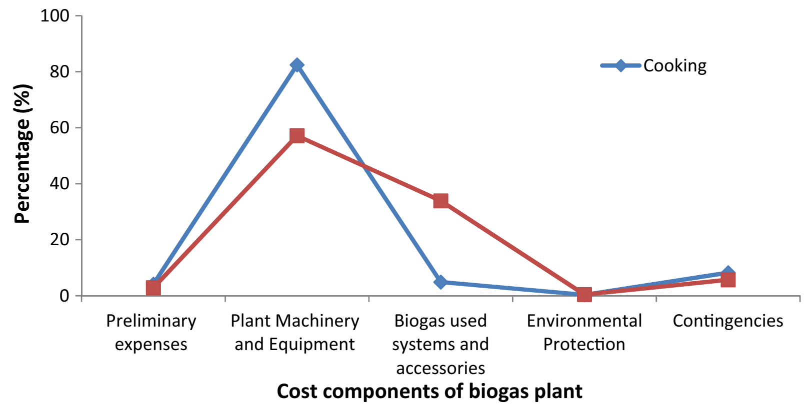

Figure 3 Percentage contributions of cost components.

Table 3 Summary of cost-benefit analysis of the 9000 m^3 biogas plant.

Components	Cooking ($)	Electricity generation ($)
Cost		
Investment cost	3,272,276	4,723,276
Total operating cost	33,050	47,705
Total cost	3,304,998	4,770,508
Benefits		
Annual cost savings from avoidance of cesspit emptying	468,440	468,440
Annual cost savings LPG production	28,301	–
Cost savings from water recycle	49,806	49,806
Cost savings from avoidance of septic tank Construction	2,070,000	2,070,000
Electricity production	–	646,780
Fertilizer production	17,069	17,069
Annual potential earnings from carbon markets (CER credits)	29,940	29,940
Total benefits	2,663,556	3,282,035
NPV	1,537,172	1,926,192
IRR	47%	29%
Discount rate	23.00%	
BCR	5.19	3.45
Payback period	5	7
Biogas plant use period	20 years	

tions, CERs) for carbon credits. According to Capoor and Ambrosi [46], the average price for CERs from developing countries like Ghana as at 2006 was at $10/tCO$_2$-e. It can be noted that GHG production of 1197.61 tonnes/year is equivalent to $29940 as potential earnings from the carbon market per annum.

Table 3 shows that the investment in biogas project at the Legon Sewerage Treatment Plant is feasible for both cooking and electricity generation options. The NPV for both scenarios was greater than zero (NPV > 0); implying that the present value of incremental benefit is greater than the present value of all investment and operating costs. Hence higher NPV values represent greater economic benefits. The BCR was also greater than one implying that for each $1 invested at a discount rate of 23%, a return of $5.19 (cooking option) and $3.45 (electricity generation) was obtained. From an investment point of view, all the two options satisfied the economic viability of all the decision criteria of CBA. Of the two options, biogas used solely for cooking (NPV $1,537,172; BCR 5.19; IRR 47%) was by far the most viable since it has a payback period of 5 years (i.e. less than half the service life). This is in agreement with research in Ghana indicating that majority of the biogas plants are for bio-sanitation interventions such as waste or effluent treatment plants [12] and this has been partially attributed to community acceptance of the use of biogas for cooking. Henceforth, the cooking option might not be the most viable option.

3.3. Sensitivity analysis

In most developing countries including Ghana, because of inflation and other economic indicators the currency is weak. In accordance, in Ghana, due to the instability of the exchange rate and its consequence effects on other items such as plant machinery and equipment, it was deemed necessary to investigate the sensitivity of the economic parameters to the variations of the factors impacting the economic situation. The purpose of sensitivity analysis was to identify those parameters that have a significant impact on project viability over the expected range of variation of the parameters. As a result, changes were made to the financial data to ascertain the possible effect the new data will have on the financial indicators (i.e. NPV and IRR). The typical parameters investigated and the ranges of variation used in this study are given in Table 4.

Table 4 Sensitivity analysis parameters.

Factor investigated	% Of base value (NPV)	% Of base value (IRR)
Pre-production cost	−25 to +25	−15 to +15
Cost of plant	−25 to +25	−15 to +15
Operating cost	−25 to +25	−15 to +15
Cost of capital	−25 to +25	−15 to +15
Systems and accessories	−25 to +25	−15 to +15
CER credits	−25 to +25	−15 to +15
Environmental protection	−25 to +25	−15 to +15
Contingencies	−25 to +25	−15 to +15

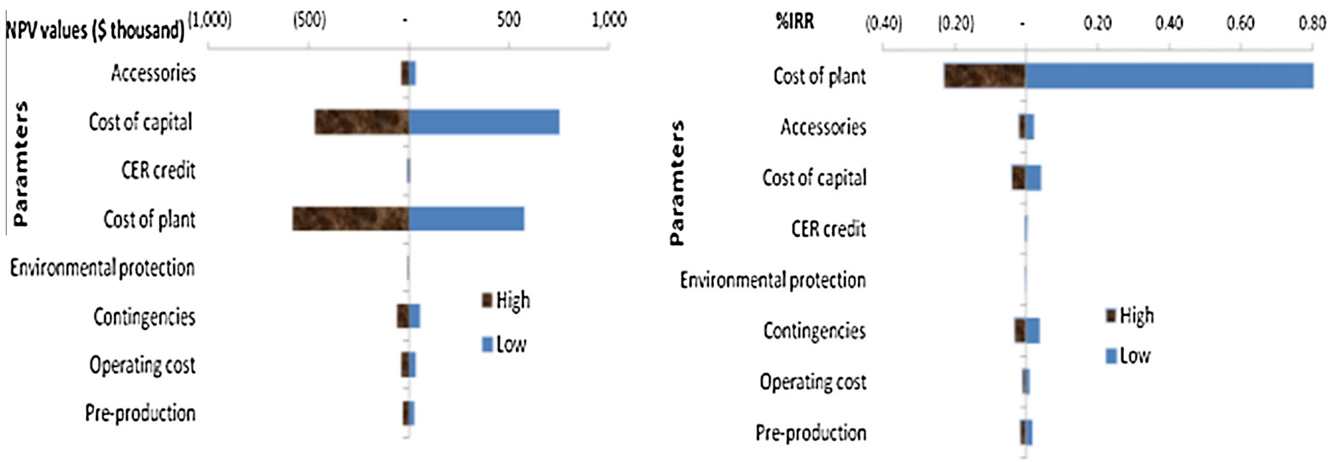

Figure 4 (a) NPV tornado chart – cooking option and (b) IRR tornado chart – cooking option.

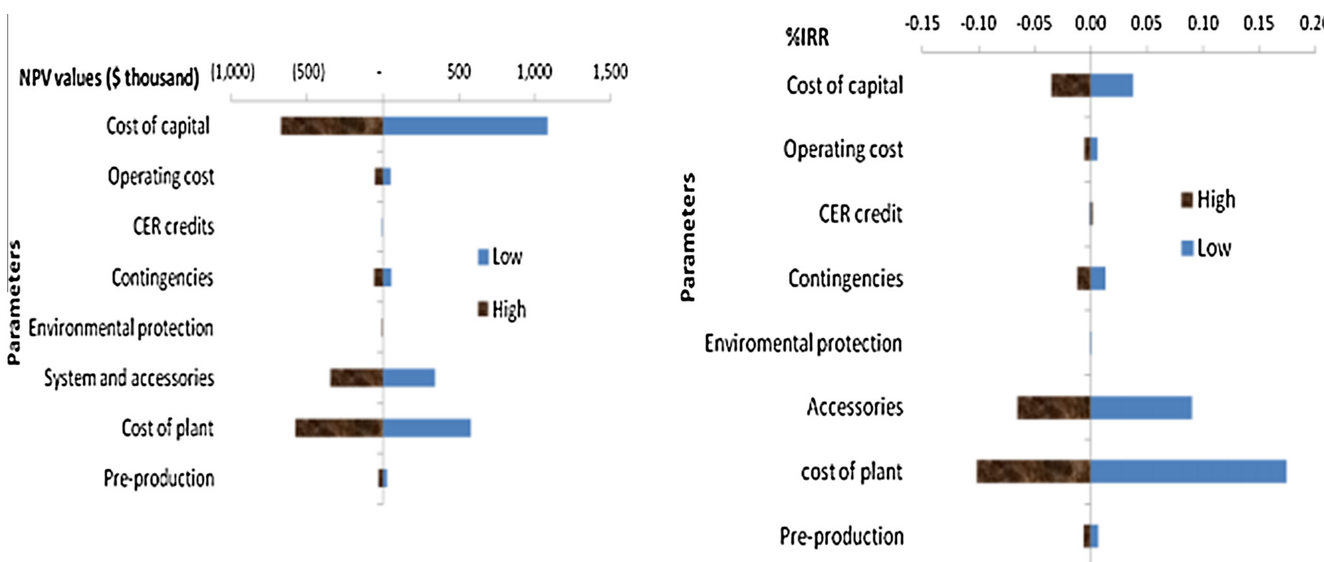

Figure 5 (a) NPV tornado chart – electricity generation option and (b) IRR tornado chart – electricity generation option.

Table 5 Single factor sensitivity analysis for cooking option.

Input variables	NPV output value ($ thousands)			% IRR output value	
	Base	Low	High	Low	High
Pre-production cost	135.00	1566.07	1508.28	48.46	44.86
Operating cost	33.05	1572.67	1501.53	47.58	45.65
Cost of capital	1537.10	2287.90	1069.28	50.84	42.61
Contingencies	266.00	1594.11	1480.24	50.36	43.26
CER credit	29.94	1531.09	1543.26	46.22	47.00
Accessories	160.28	1571.48	1502.87	48.82	44.55
Environmental protection	11.00	1539.53	1534.82	46.76	46.46
Cost of plant	2700.00	2115.07	959.28	133.00	24.00

These were then presented in tornado diagrams which are highly effective for sensitivity and risk management analyses by comparing the relative importance of the variables. The sensitivity variable was modelled as uncertain value while all other variables were kept as baseline values. Thus sensitivity analysis conducted on the two options also showed that the cooking option was the most viable.

The one way sensitivity analysis was used to investigate the impact that changes in a certain parameter will have on the model and presented in a tornado diagram, Figs. 4 and 5. This

Table 6 Single factor sensitivity analysis for electricity generation option.

Input variables	NPV output value ($ thousands)			% IRR output value	
	Base	Low	High	Low	High
Pre-production cost	135.00	1955.09	1897.30	29.83	28.55
Operating cost	47.71	1977.43	1874.75	29.78	28.59
Cost of capital	1926.19	3009.15	1255.82	32.91	25.66
Contingencies	266.00	1983.12	1869.26	30.48	27.96
CER credit	29.94	1920.12	1932.28	29.05	29.32
Accessories	1603.28	2269.35	1583.03	38.20	22.62
Environmental protection	19.00	1930.26	1922.12	29.28	29.10
Cost of plant	2700.00	2504.09	1348.30	46.61	19.06

was performed by varying the value of one of the concerned input variable in the model while keeping all other variable parameters at their base values, and the impact that the change has on the model's result. These were performed for various specified ranges of the input variable parameters depicted in Table 4 and the results recorded in Tables 5 and 6 indicating the low and high values of NPV and %IRR.

From Tables 5 and 6, it was observed that the only differences in the base values for the two scenarios were the operating cost, cost of capital and accessories. It was also established that the input variable associated with the maximum swing is the cost of capital for both NPV and IRR for cooking option. However, for the electricity option, the tornado charts showed that the highest IRR is for the cost of plant followed by accessories. Likewise the highest present worth is for the cost of plant. It was then concluded that, cost of plant and cost of capital were the most influential single input variables that had an impact on both NPV and IRR.

4. Conclusion

The investment understudy is sufficiently profitable for both scenarios in terms of NPV, profitability and pay-back. The analysis ranked the cooking option as the most viable to adopt. In addition, the sensitivity analysis revealed that cost of plant and cost of capital were the highest ranking single input variables that had significant impact on NPV and IRR using tornado diagrams. In economic terms the alternative option of installing waste stabilization ponds for treatment without biogas recovery, the minimum required by law seems less profitable than the implementation of anaerobic digestion system. Moreover, the revenue generated in terms of electricity and gas for cooking could help to finance investment made in the biogas plant. This could take care of the operation and maintenance issues. In view of the foregoing it is recommended developing nations could reconsider biogas option as alternate renewable energy. In particular, we also think that in Ghana, promoting the installation of biogas plants will help the government in achieving its 2% penetration of biogas for cooking by 2020.

Acknowledgements

This research was carried out as part of the African Water Facility (AWF) and Africa Developments Bank (AfDB) funded project dubbed "*Design for reuse – harvesting the value of effluent and nutrients for sustaining the operation of sanitation facilities*", implemented by the International Water Management Institute (IWMI). The authors would like to thank John A. Idan of BTAL for his support in providing the data for financial analysis.

References

[1] Qi Xinshan, S. Zhang, Y. Wang, R. Wang, Advantages of the integrated pig-biogas-vegetable greenhouse system in North China, Ecol. Eng. 24 (24) (2005) 177–185.

[2] H. Pathak, N. Jain, A. Bhatia, S. Mohanty, N. Gupta, Environ. Monit. Assess. 157 (2009) 407–418.

[3] M.A.C. Schouten, R.W. Mathenge, Communal Sanitation alternatives for slums: a case study of Kibera, Kenya, Phys. Chem. Earth 35 (13–14) (2010) 815–822.

[4] N. Estoppey, Evaluation of Small-Scale Biogas Systems for the Treatment of Faeces and Kitchen Waste: Case Study Kochi, South India, Swiss Federal Institute of Aquatic Science and Technology, Eawag, Dubendorf, Switzerland, 2010.

[5] R.M. Jingura, R. Matengaifa, Renew. Sustain. Energy Rev. 13 (2009) 1116–1120.

[6] S.S. Kapdi, V.K. Vijay, S.K. Rajesh, R. Prasad, Renew. Energy 30 (2005) 1195–1201.

[7] C. Müller, Anaerobic Digestion of Biodegradable Solid Waste in Low and Middle-Income Countries, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Department of Water and Sanitation in Developing Countries (Sandec), Switzerland, 2007.

[8] P. Börjesson, M. Berglund, Biomass Bioenergy 30 (2006) 469–485.

[9] P. Weiland, State of the Art of Solid-State Digestion-Recent Developments, In: Rohstoffe, F.N. (Ed.), Solid-State Digestion-State of the Art and Further R&D Requirements, vol. 24. Gulzower Fachgespräche (2006) pp. 22–38.

[10] J. Murphy, R. Braun, P. Weiland, A. Wellinger, Biogas from crop digestion. IEA bioenergy, 2011. Available from: <http://www.iea-biogas.net/technical-brochures.html> (accessed: 15.01.16).

[11] T. Amon, B. Amon, V. Kryvoruchko, W. Zollitsch, K. Mayer, L. Gruber, Agric. Ecosyst. Environ. 118 (2007) 173–182.

[12] E.C. Bensah, A. Brew-Hammond, Int. J. Energy Environ. 1 (2) (2010) 277–294.

[13] P. Drechsel, A. Olaleye, A. Adeoti, L. Thiombiano, B. Barry, K. Vohland, Adoption driver and constraints of resource conservation technologies in Sub-Saharan Africa, 2005. Available from: <http://www.iwmi.cgiar.org/africa/west/pdf/AdoptionConstraints-Overview.pdf> (accessed 12.12.15).

[14] M. Mendola, Food Pol. 32 (2007) 372–393.

[15] J.F.K. Akinbami, M.O. Ilori, T.O. Oyebisi, I.O. Oyebisi, O. Adeoti, Renew. Sustain. Energy Rev. 5 (2001) 97–112.

[16] S. Karekezi, Energy Pol. 30 (2002) 1059–1069.

[17] A.G. Mwakaje, Renew. Sustain. Energy Rev. 12 (2008) 2240–2252.
[18] S. Fleke, T. Zegeye, Food Pol. 31 (2006) 442–457.
[19] J.K. Kim, B.R. Oh, Y.N. Chun, S.W. Kim, J. Biosci. Bioeng. 102 (2006) 328–332.
[20] S.K. Sikdar, P. Glavic, R. Jain, Technological Choices for Sustainability, vols. 42–43, Springer-Verlag Berlin Heidelberg, New Work, 2004, pp. 305–307.
[21] A.K. Jha, J. Li, L. Nies, L. Zhang, Afr. J. Biotechnol. 10 (2011) 14242–14253.
[22] C. Nelson, J. Lamb, Final report: Haubenschild farms anaerobic digester updated, Available online at the Minnesota project, <www.mnproject.org>, 2002 (accessed 10.01.16).
[23] D. Meyer, J. Lorimor, Field Experiences with Two Iowa Dairy Farm Plug-Flow Digesters, ASEA Paper 034012, Iowa State Cooperative Extension, Ames, IA, 2003.
[24] A.B. Karki, N.S. Jagan, B.Sundar, Biogas: As Renewable Source of Energy in Nepal: Theory and Development, BSP-Nepal, July 2005.
[25] O. Adeoti, M.O. Ilori, T.O. Oyebisi, L.O. Adekoya, Engineering design and economic evaluation of a family-sized biogas project in Nigeria, Technovation 20 (2000) 103–108.
[26] Netherlands Development Organisation (SNV), Biogas for Better Life – an African Initiative, Business Plan (2006–2020), Available from: <https://www.biogasafrica.org/Documents/Biogas-for-Better-Life-Business-Plan-2006-2020.pdf>, 2007 (accessed 05.12.15).
[27] R. Arthur, Feasibility Study for Institutional Biogas Plant for KNUST Sewage Treatment Plant (Unpublished MSc Thesis), Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, 2009.
[28] Kumasi Institute of Technology, Energy and Environment (KITE), Feasibility Study Report on Domestic Biogas in Ghana, Accra, Ghana, Submitted to Shell Foundation, 2008.
[29] G. Johanna, J. Maria, Evaluation of a Biogas Plant in Adeiso Ghana (MSc Thesis), Swedish University of Agricultural Sciences, Faculty of Natural Resources and Agricultural Sciences, 2012.
[30] E.C. Bensah, Technical Evaluation and Standardization of Biogas Plants in Ghana (MSc Thesis), Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana, 2009.
[31] G. Hutton, E. Rehfuess, F. Tediosi, S. Weiss, Cost-Benefit Analysis of Household Energy and Health Interventions at Global and Regional Levels, World Health Organization, Geneva, 2006.
[32] J.R. Hough, Educational Cost Benefit Analysis: Education Research Paper No. 02, Loughborough University, London, 1993.
[33] S.G. Hosking, M. Du Preez, A Cost Benefit Analysis of the Working for Water Programme on Selected Sites in South Africa, University of Port Elizabeth, Department of Economics and Economic History, 30, vol. 2, (2004) 143–152.
[34] U. Marchaim, Biogas Processes for Sustainable Development, FAO Agric. Serv. Bull. 95 (1992).
[35] B. Amigun, H. von Blottnitz, Energy Convers. Manage 48 (2007) 3090–3094.
[36] African Development Bank (AfDB), Accra Sewerage Improvement Project (ASIP): Appraisal Report, 2005.
[37] S.K. Agodzo, F.P. Huibers, F. Chenini, J.B. van Lier, A. Duran, Use of Wastewater in Irrigated Agriculture, Country Studies from Bolivia, Ghana and Tunisia, vol. 2, WUR WUR (W4F – wastewater), Ghana, Wageningen, 2003.
[38] J.P. Gittinger, Economic Analysis of Agricultural Project, second ed., The John Hopkins University Press, Baltimore, USA, 1982.
[39] A. Chauvel, G. Fournier, C. Raimbault, Manual of Process Economic Evaluation, first ed., Editions TECHNIP. Institut Francais du Petrole Publications, Paris, 2003.
[40] M. Zamorano, J.L. Pérez, I. Aguilar, A. Ramos, Study of the energy potential of the biogas produced by an urban waste landfill in Southern Spain, Renew. Sustain. Energy Rev. 11 (5) (2007) 909–922.
[41] C. Washenfelder, The Economics of Biogas in the Hog Industry, A Report Prepare for Natural Resources Canada, by The Canadian Agricultural Energy End Use Data and Analysis Centre, 1999.
[42] E.K. Yiridoe, R. Gordon, B.B. Brown, Energy Pol. 37 (3) (2009) 1170–1179.
[43] C. Kandpal, J. Bharati, C.S. Sinha, Economics of Family Sized Biogas Plants in India, Energy Convers. Manage. 32 (1991) 101–113.
[44] Biogas Technologies Africa Limited (BTAL), Personal communication, A Local Company in the Design and Construction of Biogas Plants in Ghana, 2012.
[45] State Department for Statistics of Georgia, Georgian Households 1996–2001, Tbilisi, 2001.
[46] K. Capoor, P. Ambrosi, State and Trends of the Carbon Market 547, World Bank, Washington, D.C., 2007.

Please cite this article in press as: M. Mohammed et al., Feasibility study for biogas integration into waste treatment plants in Ghana, Egypt. J. Petrol. (2016), http://dx.doi.org/10.1016/j.ejpe.2016.10.004